



TITLE:

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CITATION:

Mori, Shingo. Orbital Gauss sums associated with the space of binary cubic forms over a finite field (Automorphic forms, automorphic representations and related topics). 数理解析研究所講究録 2010, 1715: 32-36

ISSUE DATE:

2010-10

URL:

<http://hdl.handle.net/2433/170304>

RIGHT:

Orbital Gauss sums associated with the space of binary cubic forms over a finite field

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§0 Introduction

We consider an orbital L -function associated with the space of binary cubic forms over rational integer ring. The orbital L -function satisfy a functional equation. The functional equation may be expressed in terms of an orbital Gauss sum. In this paper, we shall evaluate the orbital Gauss sum.

Notation. If K is a field, K^\times is its group of units and $M_n(K)$ is the ring of $n \times n$ matrices over K . When K is commutative, $GL_n(K)$ is the group of $n \times n$ matrices over K which are invertible. We use the notation $B(K)$ and $N(K)$ for the subgroups of $GL_n(K)$ of matrices of the form

$$\begin{pmatrix} * & * \\ 0 & * \end{pmatrix}, \quad \begin{pmatrix} 1 & * \\ 0 & 1 \end{pmatrix}$$

respectively. Unless otherwise specified, $G_K = G(K) = GL_2(K)$.

Let χ be a Dirichlet character of conductor f . An usual Gauss sum is defined by

$$\tau(\chi) = \sum_{a=1}^f \chi(a) \exp\left(\frac{2\pi\sqrt{-1}}{f}\right).$$

§1 The space of binary cubic forms over a finite field.

First, a review of the basic theory is in order. Let K be a field. The space V_K of binary cubic forms with coefficients in the field K is of four dimensional, and we shall identify a 4-tuple $x = (x_1, x_2, x_3, x_4) \in K^4$ with the form given by:

$$F_x(u, v) = x_1 u^3 + x_2 u^2 v + x_3 u v^2 + x_4 v^3.$$

We shall define an action of the group $G_K = GL_2(K)$ on V_K by the following functional equation:

$$F_{g \cdot x} = (\det g)^{-1} F_x((u, v) \begin{pmatrix} a & b \\ c & d \end{pmatrix})$$

where x is any element of V_K and $g = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$ is any element of G_K . This is arranged so that $\begin{pmatrix} a & 0 \\ 0 & a \end{pmatrix} \cdot x = ax$. Let $P(x)$ denote the discriminant of the form F_x , explicitly given by

$$P(x) = x_2^2 x_3^2 + 18x_1 x_2 x_3 x_4 - 4x_2^3 x_4 - 4x_1 x_3^3 - 27x_1^2 x_4^2.$$

The hypersurface $S_K = \{x \in V \mid P(x) = 0\}$ is invariant under G_K . Let V'_K denote the set of all nonsingular forms in V_K , $V'_K = \{x \in V_K \mid P(x) \neq 0\} = V_K - S_K$. A basic feature of this representation is that

$$P(g \cdot x) = (\det g)^2 P(x).$$

A non zero rational function $R(x)$ on V_K is called a relative G_K -invariant if there exists a character χ of G_K such that $R(g \cdot x) = \chi(g)R(x)$ for all $x \in V_K$ and $g \in G_K$. The discriminant generates the ring of relative invariants of this representation of $GL_2(K)$.

§2

Let p be a prime number. We shall assume that $p \neq 2, 3$. Let \mathbb{F}_q be the finite field of prime power of order q . We put $K = \mathbb{F}_q$. The hypersurface S_K and nonsingular set V'_K decomposes into three G_K orbits.

Lemma 1. *We put $s_1 = (1, 0, 0, 0)$ and $s_2 = (0, 1, 0, 0)$. The G_K -orbits in S_K are precisely*

$$S_0 = \{0\};$$

$$S_1 = G_K \cdot s_1 = \{x \in V_K \mid F_x \text{ has a triple root}\};$$

$$S_2 = G_K \cdot s_2 = \{x \in V_K \mid F_x \text{ has a double root and a distinct simple root}\}.$$

For a form x in V'_K , let $K(x)$ denote the cubic ring of x over K . The degree of $K(x)$ is 3.

Lemma 2. *Two nonsingular binary cubic forms over \mathbb{F}_q are G_K -equivalent if and only if their cubic ring are same. The G_K -orbits in V'_K are precisely*

$$V'_{K,1} = \{x \in V'_K \mid \mathbb{F}_q(x) = \mathbb{F}_q \times \mathbb{F}_q \times \mathbb{F}_q\};$$

$$V'_{K,2} = \{x \in V'_K \mid \mathbb{F}_q(x) = \mathbb{F}_{q^2} \times \mathbb{F}_q\};$$

$$V'_{K,3} = \{x \in V'_K \mid \mathbb{F}_q(x) = \mathbb{F}_{q^3}\}.$$

The order of stabilizer in G_K of nonsingular binary cubic forms with cubic ring $\mathbb{F}_q \times \mathbb{F}_q \times \mathbb{F}_q$, $\mathbb{F}_{q^2} \times \mathbb{F}_q$ and \mathbb{F}_{q^3} is 6, 2 and 3, respectively. If $p \equiv 1 \pmod{3}$, there are three nonsingular G_K -orbits with representatives:

$$x_I = (1, 0, -1, 0), \quad x_{II} = (r, 0, -1, 0), \quad x_{III} = (s, 0, 0, -1),$$

where r is any element of \mathbb{F}_q^\times that is not a square and s is any element that is not a cube.

§3 The orbital Gauss sum.

For simplicity, we shall assume that $K = \mathbb{F}_p$. Let ψ be a character of multiplicative group of \mathbb{F}_p^\times of nonzero elements of \mathbb{F}_p . Extend ψ to \mathbb{F}_p by the convention $\psi(0) = 0$. The alternating form:

$$[x, y] = x_1 y_4 - \frac{1}{3} x_2 y_3 + \frac{1}{3} x_3 y_2 - x_4 y_1,$$

has the property that $[g \cdot x, \det(g)^{-1} g \cdot y] = [x, y]$ for all $x, y \in V_K$ and $g \in G_K$. For $x, y \in V_K$, we put

$$\langle x, y \rangle = \exp\left(\frac{2\pi\sqrt{-1}}{p}[x, y]\right).$$

We define the orbital Gauss sum.

Definition 1. For $a, b \in V_K$, we define

$$W(\psi, a, b) = \sum_{g \in G_K} \psi(\det(g)) \langle x, g \cdot y \rangle$$

After basic calculation, we find that

$$W(\psi, g \cdot a, g' \cdot b) = \psi(\det g)^{-1} \psi(\det g')^{-1} W(\psi, a, b)$$

where $g, g' \in G(K)$. We can take the following set:

$$V(\mathbb{F}_p) = \{y_0 | y_0 \in S_0\} \sqcup \{y_1 | y_1 \in S_1\} \sqcup \{y_2 | y_2 \in S_2\} \sqcup \{y_3 | y_3 \in V'_{1,K}\} \sqcup \{y_4 | y_4 \in V'_{1,K}\} \sqcup \{y_5 | y_5 \in V'_{1,K}\}.$$

For positive integers i, j , $0 \leq i, j \leq 5$, we define a matrix valued Gauss sum $W(\psi)$ as a 6×6 matrix whose (i, j) component is given by $\frac{1}{\#G(K)_{y_j}} W(\psi, y_i, y_j)$.

We shall assume that $\psi^3 = 1$. Our main result is as follows.

Theorem 1. Let ψ be a trivial character. If $p \equiv 1 \pmod{3}$, then

$$W(1) = \begin{pmatrix} 1 & p^2 - 1 & p(p^2 - 1) & \frac{1}{6}p(p^2 - 1)(p - 1) & \frac{1}{2}p(p - 1)(p^2 - 1) & \frac{1}{3}p(p - 1)(p^2 - 1) \\ 1 & -1 & p(p - 1) & \frac{1}{6}p(p - 1)(2p - 1) & -\frac{1}{2}p(p - 1) & -\frac{1}{3}p(p^2 - 1) \\ 1 & p - 1 & p(p - 2) & -\frac{1}{2}p(p - 1) & -\frac{1}{2}p(p - 1) & 0 \\ 1 & 2p - 1 & -3p & \frac{1}{6}p(p + 5) & -\frac{1}{2}p(p - 1) & \frac{1}{3}p(p - 1) \\ 1 & -1 & -p & -\frac{1}{6}p(p - 1) & \frac{1}{2}p(p + 1) & -\frac{1}{3}p(p - 1) \\ 1 & -p - 1 & 0 & \frac{1}{6}p(p - 1) & -\frac{1}{2}p(p - 1) & \frac{1}{3}p(p + 2) \end{pmatrix}.$$

If $p \equiv 2 \pmod{3}$, then

$$W(1) = \begin{pmatrix} 1 & p^2 - 1 & p(p^2 - 1) & \frac{1}{6}p(p^2 - 1)(p - 1) & \frac{1}{2}p(p - 1)(p^2 - 1) & \frac{1}{3}p(p - 1)(p^2 - 1) \\ 1 & -1 & p(p - 1) & \frac{1}{6}p(p - 1)(2p - 1) & -\frac{1}{2}p(p - 1) & -\frac{1}{3}p(p^2 - 1) \\ 1 & p - 1 & p(p - 2) & -\frac{1}{2}p(p - 1) & -\frac{1}{2}p(p - 1) & 0 \\ 1 & 2p - 1 & -3p & \frac{1}{6}p(-p + 5) & \frac{1}{2}p(p + 1) & -\frac{1}{3}p(p + 1) \\ 1 & -1 & -p & \frac{1}{6}p(p + 1) & \frac{1}{2}p(-p + 1) & \frac{1}{3}p(p + 1) \\ 1 & -p - 1 & 0 & -\frac{1}{6}p(p + 1) & \frac{1}{2}p(p + 1) & \frac{1}{3}p(p - 2) \end{pmatrix}.$$

Theorem 2. Let ψ be a nontrivial cubic character. If $p \equiv 1 \pmod{3}$, then

$$W(\psi) = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & p\tau(\bar{\psi}) & 0 & \frac{1}{6}p(p-1)\tau^2(\psi) & -\frac{1}{2}\psi(4r)p(p-1)\tau^2(\psi) & \frac{1}{3}\bar{\psi}(s)p(p-1)\tau^2(\psi) \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \tau^2(\psi) & 0 & \frac{1}{6}A & \frac{1}{2}X & \frac{1}{3}B \\ 0 & -\psi(4r)\tau^2(\psi) & 0 & \frac{1}{6}X & \frac{1}{2}Y & \frac{1}{3}D \\ 0 & \bar{\psi}(s)\tau^2(\psi) & 0 & \frac{1}{6}B & \frac{1}{2}D & \frac{1}{3}C \end{pmatrix}$$

where

$$\begin{aligned} A &= \tau^4(\bar{\psi}) + 4\tau^2(\psi) - \frac{\tau^5(\psi)}{p}, \quad B = \bar{\psi}(s) \left(\tau^4(\bar{\psi}) - 2\tau^2(\psi)p - \frac{\tau^5(\psi)}{p} \right), \\ C &= \psi(s) \left(\tau^4(\bar{\psi}) + \tau^2(\psi)p - \frac{\tau^5(\psi)}{p} \right), \quad D = \psi(4rs^2) \left(\tau^4(\bar{\psi}) + \frac{\tau^5(\psi)}{p} \right), \\ X &= \psi(4r) \left(\tau^4(\bar{\psi}) + \frac{\tau^5(\psi)}{p} \right) \text{ and } Y = \tau^4(\bar{\psi}) - \frac{\tau^5(\psi)}{p}. \end{aligned}$$

Proofs. For simplicity we assume $a = b = s_1$. We put $w = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$. Elementary methods of linear algebra give the Bruhat decomposition

$$G(K) = B(K) \sqcup B(K)wN(K)$$

where

$$\begin{aligned} B(K) &= \left\{ \begin{pmatrix} a & 0 \\ 0 & c \end{pmatrix} \begin{pmatrix} 1 & n \\ 0 & 1 \end{pmatrix} \mid a, c \in K^\times, n \in K \right\} \\ \text{and } B(K)wN(K) &= \left\{ \begin{pmatrix} a & 0 \\ 0 & c \end{pmatrix} \begin{pmatrix} 1 & n \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 1 & m \\ 0 & 1 \end{pmatrix} \mid a, c \in K^\times, n, m \in K \right\}. \end{aligned}$$

For $g_1 \in B(K)$ and $g_2 \in B(K)wN(K)$, we define

$$W_1(\psi, s_1, s_1) = \sum_{g_1 \in B(K)} \psi(\det g_1) \langle [s_1, g_1 \cdot s_1] \rangle$$

and

$$W_2(\psi, s_1, s_1) = \sum_{g_2 \in B(K)wN(K)} \psi(\det g_2) \langle [s_1, g_2 \cdot s_1] \rangle.$$

For $1 \leq i \leq 2$, the twisted action of g_i on the element s_1 is given by $g_1 \cdot s_1 = (a^2c^{-1}, 0, 0, 0)$, $g_2 \cdot s_1 = (a^2c^{-1}n^3, 3an^2, 3an, a^{-1}c^2)$. A straightforward calculation shows that

$$\begin{aligned} W_1(\psi, s_1, s_1) &= \sum_{g \in B(K)} \psi(\det g) \langle [s_1, g_i \cdot s_1] \rangle \\ &= \sum_{a, c \in K^\times, n \in K} \psi(ac) \langle 0 \rangle \\ &= \begin{cases} (p-1)^2p & \text{if } \psi = 1, \\ 0 & \text{otherwise.} \end{cases} \end{aligned}$$

We deduce the analogous equality for $W_2(\psi, s_1, s_1)$

$$\begin{aligned}
 W_2(\psi, s_1, s_1) &= \sum_{g \in B(K) \backslash wN(K)} \psi(\det g) \langle [s_1, g_i \cdot s_1] \rangle \\
 &= \sum_{a, c \in K^\times, n, m \in K} \psi(ac) \langle a^{-1}c^2 \rangle \\
 &= \sum_{a, c \in K^\times, n, m \in K} \psi(ac^3) \langle a^{-1} \rangle \\
 &= \sum_{a, c \in K^\times, n, m \in K} \bar{\psi}(a) \langle a \rangle \\
 &= p^2(p-1)\tau(\bar{\psi}).
 \end{aligned}$$

Combining all these equalities, we obtain

$$W(\psi, s_1, s_1) = W_1(\psi, s_1, s_1) + W_2(\psi, s_1, s_1) = \begin{cases} -p(p-1) & \text{if } \psi = 1, \\ p^2(p-1)\tau(\bar{\psi}) & \text{otherwise.} \end{cases}$$

More precious proof will be shown in [SM].

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